REPORT NO. 761

IDENTIFICATION OF KNOCK IN NACA HIGH-SPEED PHOTOGRAPHS OF COMBUSTION IN A SPARK-IGNITION ENGINE

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SUMMARY

The study of combustion in a spark-ignition engine given in NACA reports 704 and 727 has been continued. The present investigation was made with the NACA high-speed motion-picture camera, operating at 40,000 photographs a second, and with a cathode-ray oscillograph operating on a piezoelectric pickup in the combustion chamber.

Identity in time is established between the start of violent pressure fluctuations in the combustion chamber and the appearance of blur in the high-speed schlieren photographs. The blur was tentatively presumed to represent the occurrence of knock in the previous reports.

Photographs are presented showing that the origin of knock is not necessarily in the end gas.

The data obtained indicate that knock takes place only in a part of the cylinder charge which has been previously ignited either by autoignition or by the passage of the flame fronts but which has not burned to completion.

Mottled regions in the high-speed schlieren photographs are demonstrated to represent combustion regions.

INTRODUCTION

In 1938 the National Advisory Committee for Aeronautics completed the development of the NACA high-speed motion-picture camera, which takes photographs at the rate of 40,000 per second. This camera has been used since that time in the study of combustion in a spark-ignition engine. The first results of the study with this camera were published in 1941 (reference 1). These results consisted of photographs of normal and knocking combustion with one spark plug and of normal and knocking combustion with preignition from a hot spot, also with one spark plug. The photographs were taken by the schlieren method, which utilizes variations of index of refraction in the combustion chamber to form an image on the photosensitive film.

The most interesting indications of these photographs in connection with normal combustion were that the combustion zone has considerable depth in the direction of flame travel and that the depth of combustion zone decreases during the latter part of the flame travel. It was pointed out in reference 1 that the apparent depth of the combustion zone might possibly be explained by the tonguing of the flame front or by hypothetical temperature stratifications that required a considerable time for decay after the passage of the flame front.

The most important indication of the photographs of combustion with knock was that autoignition might occur in the end zone before knock but not simultaneously with it. The photographs showed a sudden blurring of the combustion zone simultaneous with the beginning of a violent visible bouncing of the gases. The combustion zone disappeared from the photographs presented in reference 1 within 0.0001 second after occurrence of the blur. The blur, the disappearance of the combustion zone, and the start of the violent bouncing of the gases were tentatively assumed to be the visual evidence of knock.

The apparent occurrence of autoignition an appreciable time before knock in some cases and the complete absence of apparent autoignition in other cases of knocking combustion cast doubt on the adequacy of the simplest form of the widely accepted autoignition theory of knock, proposed by Ricardo (reference 2). According to this theory, in the cases where autoignition was observed, the autoignition and the beginning of the violent bouncing of the gases should have been much more nearly simultaneous. Rothrock and Spencer (reference 3) had previously reported failure to observe any reaction in the end zone before knock under certain conditions. The autoignition theory of knock presumes that a part of the charge in the combustion chamber has not yet been reached by the flame front at the time knock occurs. This hypothetical part of the charge is usually called the end gas. The theory is that the end gas is adiabatically compressed by the expansion of the burned part of the charge and is heated by the adiabatic compression until it reaches a combination of temperature and pressure at which it autoignites. The combustion due to autoignition is presumed to proceed to completion throughout the entire volume of the end gas so quickly that the end gas does not have time to expand during the combustion, with the result that an extremely high pressure is produced within the end gas. The subsequent violent expansion of the end gas would start the violent pressure vibrations throughout the combustion chamber, which are known to be associated with spark-ignition fuel knock. According to the simplest form of the theory, the combustion of the autoignited end gas is not of a different nature from the combustion in the normal flame except that a considerably larger mass of the

gas is involved at one time. The simplest form of the autoignition theory will hereinafter be referred to as the "simple autoignition theory."

The high-speed photographs of Withrow and Rassweiler (reference 4) have been most widely cited as proof of the autoignition theory of knock. The fact, however, that these photographs show an autoignition, with consequent pressure rise in the end gas, too slow to be very effective in causing the pressure vibrations characteristic of knock appears to have been overlooked. The engine used for the work of reference 4 had an L-head with 2⅞-inch bore, the greatest dimension within the combustion chamber being about 5.4 inches. The form of the combustion chamber does not allow a simple analytical determination of the exact natural frequency of pressure vibrations within it. A probable minimum value for the frequency of these vibrations can, however, be easily obtained.

Draper (references 5 and 6) has made calculations for the natural frequencies of various modes of knocking vibrations within cylindrical combustion chambers with flat ends, using a sound velocity of 3000 feet per second, and has obtained good agreement with experimental values. It may be observed, as might reasonably be expected, that the formulas used by him give a value of frequency never less than $n=\frac{c}{2l}$ for the lowest frequency mode of vibration, where c is the velocity of sound in feet per second and l is the maximum linear dimension within the combustion chamber in feet.

The natural frequency of the knocking vibrations in the engine used in reference 4 could not, according to this formula, be less than 3330 cycles per second. The photographs of knocking combustion appearing in reference 4 were taken at the rate of 2250 frames per second. The autoignition, seen in the photographs, usually occupies a time interval of two frames, or 0.00089 second. The lowest-frequency knocking vibrations that could exist in this chamber, therefore, must have gone through three complete cycles during the time of the autoignition that obviously took place. So slow an autoignition could impart only a small fraction of its energy to the knocking vibrations. The authors of reference 4 state that knock occurred in the combustion cycles shown by these photographs. The evidence of reference 4, therefore, suggests that the cause of knock might well be sought in some faster phenomenon than the slow autoignition shown by the photographs.

A possibility occurs that a part of the autoignition took place at a much faster rate than the rest. The photographs of reference 4, however, discourage this idea. They have stopped the autoignition in early, late, and intermediate stages. Although the photographs do not positively prove that such an extremely rapid fractional autoignition did not occur, they certainly present no evidence whatever that it did occur.

Another possibility is that a pressure wave of small amplitude, once started, accelerates the autoignition in its high-pressure region and decelerates the autoignition in its low-pressure region. This possibility is in agreement with the suggestion by Miller (reference 7) that knock may develop as the progressive build-up of a reflected pressure wave, the build-up of the wave being due to acceleration of combustion or to acceleration of some other reaction within the high-pressure region of the wave. This suggestion was based on a study of time-pressure records obtained with the NACA optical engine indicator and on a study of photographs of knocking combustion taken with the NACA high-speed motion-picture camera. The time-pressure records showed slight irregularities a short time before the occurrence of the first violent pressure fluctuation, which could be explained by progressively built-up reflected waves. The photographs observed as original negatives showed slight periodic variations in the configurations of the mottled regions, which could also be explained by the reflected waves.

The existence of pressure waves in the cylinder charge before knocking becomes audible and the fact that these pressure waves greatly increase in intensity when the characteristic sound of detonation appears have been reported by Draper (reference 5).

It is important to note that the vibrational-combustion theory of knock could still not be independent of autoignition even if it were shown not to be linked with autoignition in the manner suggested in the second paragraph preceding. Increasing severity of pressure and temperature in the combustion chamber is well known to cause increasing tendency to knock. Autoignition is known to occur under certain conditions. When it does occur it should be expected to increase the pressure and temperature in the combustion chamber so rapidly that knock will take place very soon afterward, if knock is going to take place at all. Leary and Taylor (reference 8) have shown conclusively that tendency to knock decreases with increasing rate of rise of temperature. If autoignition occurs before knock, however, so that the entire available rise in temperature takes place in an extremely short time, the knock if it occurs at all may be expected to occur during the extremely short time of that rise of temperature, even though it would have occurred at a lower temperature after a longer time without the occurrence of the autoignition. It should be expected that the rate of build-up of vibration would vary with the mass of reacting gas.

The authors of reference 1 believed that the characteristic blur and the disappearance of the mottled zone in the high-speed schlieren photographs represent the reaction that sets up the knocking vibrations because this view was supported by the appearance of the photographs projected as motion pictures. Because these phenomena occur definitely later than the apparent autoignition in the chamber, a need was felt for establishing a definite time relationship between the beginning of the violent pressure vibrations on the one hand and the occurrence of apparent autoignition, knocking blur, and the clearing of the mottled zone on the other hand.

The investigation reported in the present paper was undertaken in order to determine such a time relationship. As a corollary to this determination, a conclusion was anticipated

as to whether the observed periodic variations in the high-speed photographs before the occurrence of blur cover the same period of time as the irregularities in the time-pressure records before the beginning of violent pressure fluctuations.

Since the present paper deals with the time relationship between various phenomena and the occurrence of knock, it will be necessary to define the term "knock" as used herein. Such definition is as follows: Knock is any phenomenon of combustion occurring in the NACA combustion apparatus cylinder under any of the test conditions used which causes prolonged visible high-frequency fluctuations in the time-pressure records. Where the pressure fluctuations of the greatest amplitude in a given time-pressure record are preceded by fluctuations of smaller amplitude, the point of occurrence of knock on the given time-pressure record will be taken as the point of discontinuity in the curve preceding the pressure fluctuation of greatest amplitude. This definition of knock and this method of determining the point of occurrence of knock have been adequate to avoid confusion in the study of the records taken with the NACA combustion apparatus, the NACA high-speed camera, and a quartz-crystal piezoelectric pickup under the conditions of all tests made to the present time. It is recognized that with other apparatus or other test conditions phenomena might be encountered that would fit this definition of knock except as to apparatus or test conditions and which might be distinct from the phenomenon to which the term is applied in this paper. It is also recognized that with other apparatus or other test conditions cases of knock might be encountered in which this method of determining the point of occurrence of knock would fail.

APPARATUS AND PROCEDURE

Combustion apparatus.—The NACA combustion apparatus is described in detail in reference 1. Figure 1 of this report shows this combustion apparatus diagrammatically. At the time of taking all the photographs presented in this report an injection valve was placed in opening H. (See fig. 1.) For some of the photographs, spark plugs were placed in openings E, G, F, and J and a piezoelectric pickup was placed in opening I, its diaphragm being flush with the combustion-chamber wall. For other pictures, the spark plug was removed from opening J and the piezoelectric pickup was placed in this opening.

As in the previous investigations the combustion apparatus was driven at the test speed by an electric motor and was fired for only one cycle. During the one power cycle of the engine a single charge of fuel was injected on the intake stroke, a single spark occurred at each spark plug, an entire series of photographs of the combustion was taken, and a time-pressure record was made.

Engine operating conditions.—Engine operating conditions kept constant were: engine-coolant temperature, 250° F; compression ratio, 7.4; engine speed, 500 rpm; fuel-air ratio, approximately 0.08; spark advance in G position (see fig. 1), 29°; spark advance in E, F, and J positions, 22°. Spark advance in G position was made earlier than in the other positions in order that the flame originating at this position might come into the field of view at about the same time as the flames from the other three spark-plug positions. This arrangement brought the end zone of combustion within the field of view in as many cases as possible.

Fuels.—Fuels used were CFR reference fuels S-1 (a com-

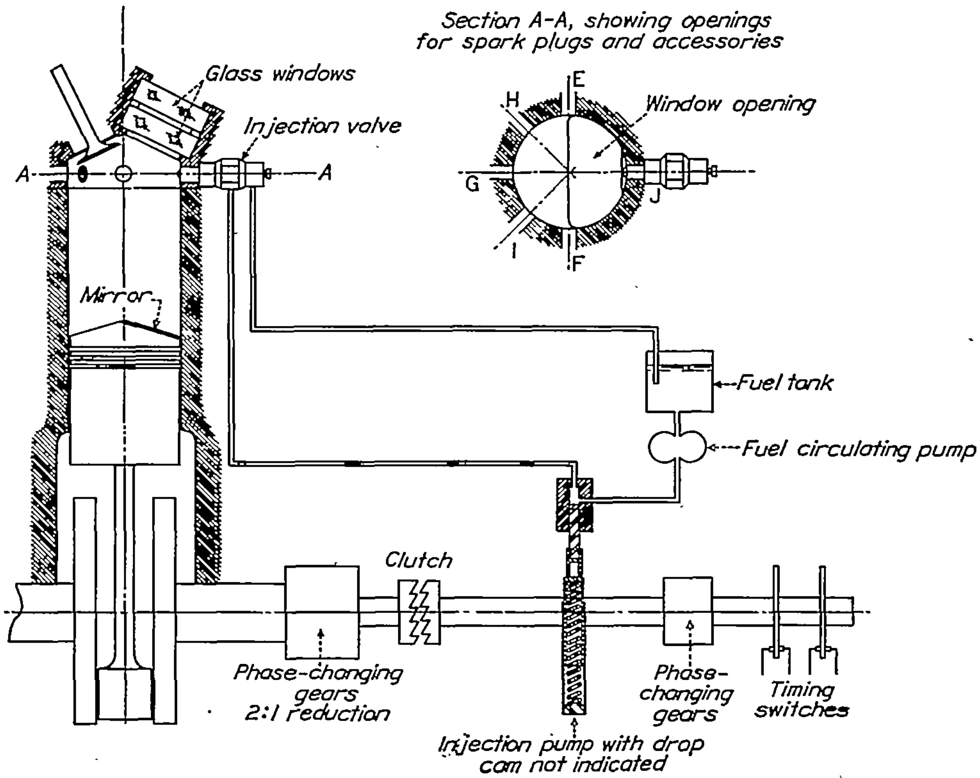


FIGURE 1.—Diagrammatic sketch of NACA combustion apparatus.

mercial grade of isooctane), M-2 (octane number about 18), and blends of these two reference fuels.

Setup for schlieren photography.—The optical setup for schlieren photography was the same as that used in the investigations reported in references 1 and 7. A complete description of this setup may be found in reference 1. The schlieren photographs of combustion were taken at the rate of 40,000 per second by the NACA high-speed motion-picture camera, complete details of which cannot be given at this time.

Time-pressure records.—Time-pressure records were made with a piezoelectric pickup using two X-cut quartz crystals in one of the spark-plug openings of the combustion apparatus and a cathode-ray oscillograph. The sweep circuit of the cathode-ray oscillograph was externally synchronized with the engine crankshaft. The brilliancy control of the oscillograph beam was arranged in such a way that the beam would normally be invisible but, when tripped by a contactor at the engine, would become brilliant for a single sweep during the single power cycle of the combustion apparatus. This single sweep of the oscillograph beam was photographed with a portrait type of "still" camera. No attempt was made to calibrate the vertical deflection of the oscillograph beam. Consequently, quantitative data concerning pressures are not available. The pressure scale is known, however, to be fairly linear.

Time relationship between time-pressure records and high-speed photographs.—A time relationship between the time-pressure records and the high-speed photographs of combustion was established by two methods. The first method involved the use of only one oscillograph. Two timing sparks were set off by the combustion apparatus: one immediately after the start of combustion, the other a considerable time after the occurrence of knock. The spark gap for these timing sparks was in a special plug provided in the high-speed camera. This spark gap was arranged to expose a small spot on the motion-picture film at a point about 33 frames behind the picture-taking point of the camera. Exposure of the timing sparks closer than 33 frames to the picture-taking point was not feasible because of structural difficulties. By counting forward 33 frames from each of the two spots on the film, datum frames were identified that were in the process of exposure when the timing sparks occurred. The timing spark lead was coupled capacitatively to the oscillograph with the result that a slight break in the time-pressure record occurred at the time of each timing spark. The points in the time-pressure record at which these breaks occurred were taken as being identical in time with the corresponding datum frames on the motion-picture film.

In order to avoid the necessity of obtaining an extremely linear oscillograph sweep and at the same time to correct for photographic distortion of the oscillograph screen, a 4000-cycle-per-second oscillator was used. The engine was stopped immediately after firing and the brilliancy control was again tripped to give a single sweep of the oscillograph beam across the zero-pressure base line. Upon this zero-pressure base line was superposed a sine wave from the oscillator. This sine wave was used to determine the time-displacement relationship for the sweep and made possible the identification of any point on the time-pressure record as simultaneous with the exposure of some particular frame on the high-speed motion-picture film.

A Hewlett-Packard oscillator, model 200C, was used. This instrument is of the relaxation-oscillation type, utilizing the periodic charging of a condenser as the generator of the oscillations. At a frequency of 4000 cycles per second the frequency may be regarded as virtually constant over the time, about 50 cycles, used in the tests presented herein. The actual frequency drift over a period of time as short as 50 cycles is probably a small fraction of 1 percent.

Because of inconsistency of results with the previously described method, possibly due to some slight reaction by the vertical deflection of the oscillograph beam on the horizontal deflection and to lack of reproducibility of the oscillograph sweep characteristics, a second method was devised for establishing the time relationship between the high-speed photographs and the time-pressure records. With this method a second oscillograph was used, arrangement being made with mirrors to photograph the screens of both oscillographs on the same film. The second oscillograph, like the first, was synchronized externally with the combustion apparatus and was arranged to have a brilliant beam for only one sweep, which occurred during the power cycle of the combustion apparatus. The second oscillograph was connected at its vertical input to the 4000-cycle oscillator but not to the piezoelectric pickup. The oscillator trace was superposed on the time-pressure record in the first oscillograph. Capacitive pickup from the timing spark lead was arranged for both oscillographs.

The trace from the second oscillograph served to determine accurately the number of oscillator cycles between timing sparks. This trace therefore allowed an accurate determination of the number of frames exposed on the high-speed motion-picture film per oscillator cycle. On the time-pressure record the number of oscillator cycles between the break caused by the first timing spark and the beginning of the violent pressure fluctuations could be counted more easily and accurately than in the case where the two traces were not superposed. Determination of the number of cycles in this part of the time-pressure record made possible the identification of the frame on the high-speed motion-picture film that was exposed at the time the violent pressure fluctuations began at the diaphragm of the piezoelectric pickup, with a possible error of only one or two frames. Inasmuch as each oscillograph trace carried its own time scale, variations in sweep characteristics were of no consequence either as between the two oscillographs or as between successive sweeps of the same oscillograph beam. The oscillograph which carried the oscillator trace alone could have been dispensed with in the second method except that oscillator cycles could not be identified on the time-pressure record after the beginning of the violent pressure fluctuations. For the camera used, the picture-taking rate is constant, for a single series of photographs, within a small fraction of 1 percent.

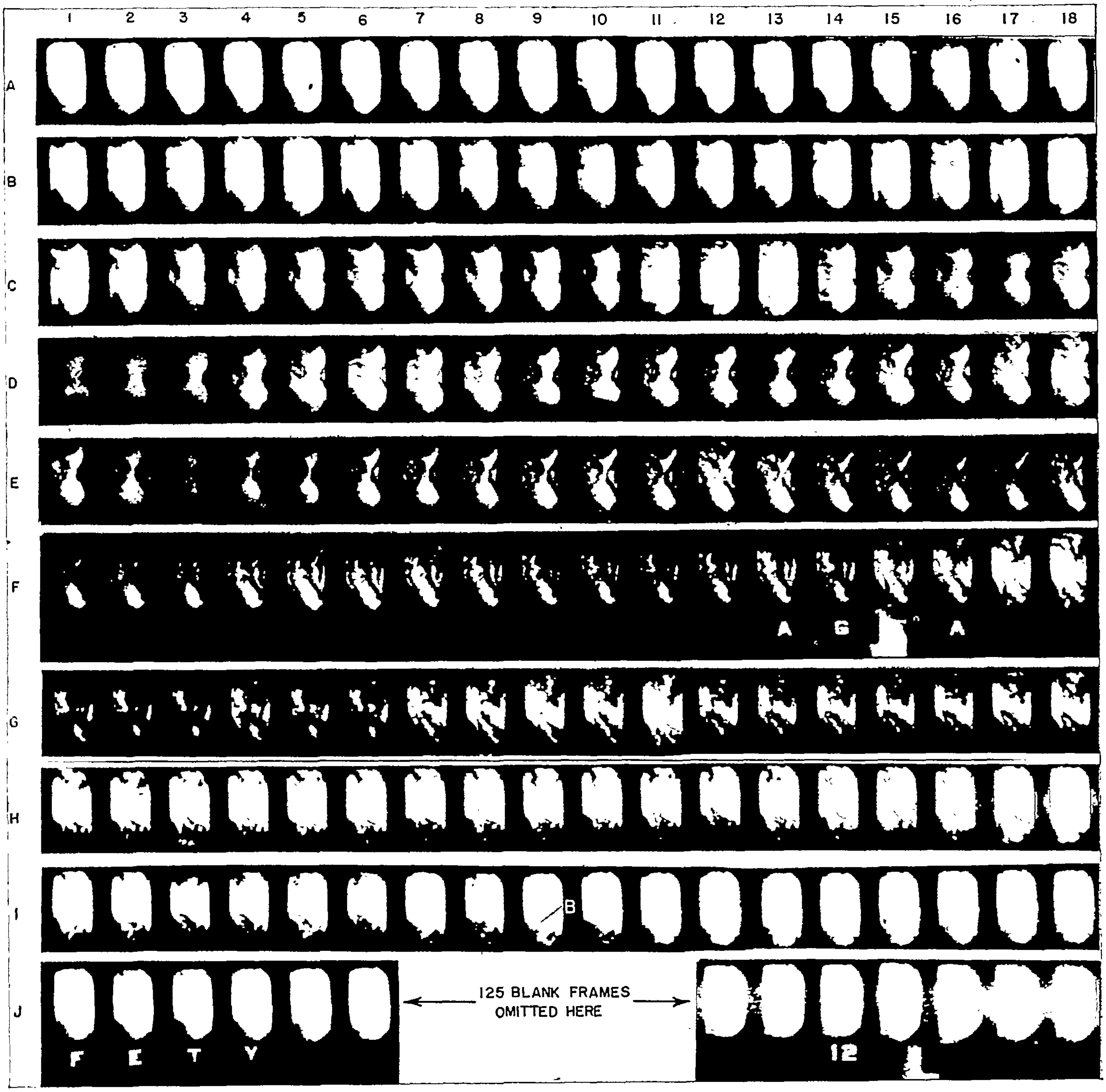


FIGURE 2.—High-speed motion pictures of an explosion in a spark-ignition engine with light knock. Fuel, 90 percent S-1 with 10 percent M-2; four spark plugs; spark advance, left hand plug, 29°, other three plugs, 22°; B, blurring caused by knock

RESULTS AND DISCUSSION

Time relationship of schlieren blur to gas vibrations—first method.—The first method of establishing time relationship is believed to be much less accurate than the second method. All results obtained with the first method are reported herein, however, in order that the authors' judgment as to which method is more dependable need not be relied upon but that each method may be given such weight by the reader as, in his judgment, it is worth.

Figure 2 is a series of photographs showing combustion with very light knock. The fuel used for this series was a blend of 90 percent S–1 and 10 percent M–2. Four spark plugs were used and the piezoelectric pickup was located in opening I of the cylinder head.

The order of the photographs is A–1, A–2, . . . A–18, B–1, . . . J–17, J–18. The film was carried on a circular drum in a continuous loop. This series, like all others that appear in this report, was therefore carried through the

picture-taking point in the camera many times; the photographs were exposed on one of the trips through the picture-taking point. One hundred and twenty-five frames, upon which combustion does not appear, were omitted in the figure between frames J–6 and J–12. Seventy-two additional frames, which would have appeared in the figure after frame J–18 or before frame A–1, were omitted. The total number of frames in the film loop was 372, as in all other cases.

The perforated edge of the film was reproduced in the figure only in rows F and J. The timing sparks caused exposures on the perforated edge in these rows. The exposure between frames J–15 and J–16 resulted from the first timing spark; the exposure at frame F–15, from the second timing spark. In the time between the first and second timing sparks, the film drum turned sufficiently to carry 551½ frames past the picture-taking point of the camera, or about 1½ turns.

At the occurrence of the first timing spark, the camera had not started taking pictures. This spark occurred 108½ frames before the exposure of frame A–1 and 261½ frames before the exposure of frame I–9, in which the characteristic knocking blur is first visible.

At the occurrence of the second timing spark the camera had ceased taking pictures. This spark occurred 372 frames (one complete turn of the film drum) after the exposure of frame D–18. Frame D–18 was 33 frames ahead of frame F–15, 33 frames being the distance from timing spark plug to picture-taking point in camera.

As in the figures of references 1 and 7, the flames appear in figure 2 as dark mottled regions. The first evidence of knock is a slight blur of a part of the dark mottled region at B in frame I–9. The knock in this case is so light that it is not readily noted by the inexperienced observer. A painstaking comparison of frames I–8 and I–9, however, will reveal a difference in the region designated B, which has no counterpart in a comparison of frames I–7 and I–8. When the photographs are projected as motion pictures, the blurred region shows unmistakably.

Figure 3 is a photograph of the oscillograph screen showing the time-pressure record for the combustion cycle photographed in figure 2. In figure 3, as in the later figures, A designates the time-pressure trace; B, the oscillator trace; and L, motoring traces that were accidentally exposed before or after the single power cycle. The letter E designates a break caused in the time-pressure trace by pickup from the earliest ignition spark, and G designates a break by pickup from the three later ignition sparks. A break in the trace caused by the first timing spark is designated F and a break caused by the second timing spark is designated J. The letter K designates the place on the time-pressure trace at which knocking vibrations first become visible.

The displacement between the successive curves L may be due to the tendency of the oscillograph beam to shift the mean vertical deflection of each sweep toward the zero-pressure base line. Whatever the reason for the irregularity may be, however, it does not appear to affect the usefulness of the combustion record as applied herein.

The preliminary ticks in the time-pressure trace just before the knocking vibrations begin, which were discussed in reference 7, are not evident in the light knocking traces with the present apparatus. (See fig. 3.) They will, however, be observed in all the traces involving violent knock.

In figure 3, lines have been drawn from points F, K, and J to the points in the oscillator trace that correspond with them

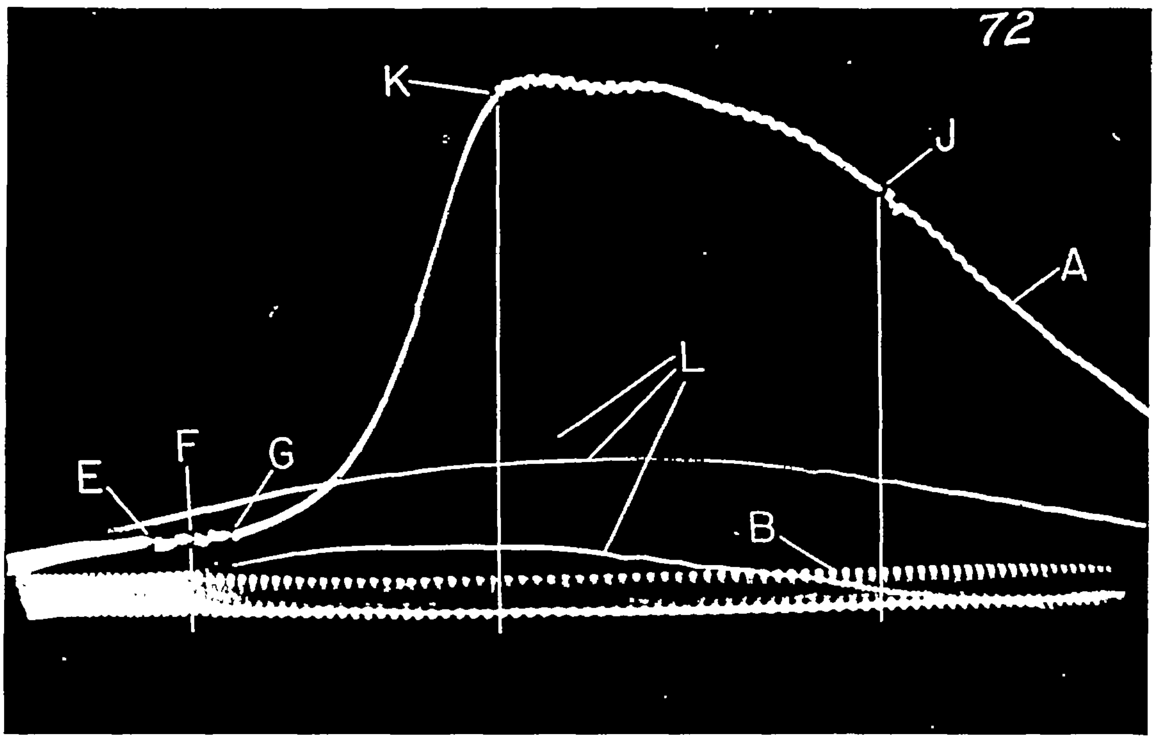


FIGURE 3.—Indicator card with oscillator trace for explosion of figure 2 in a spark-ignition engine with light knock. Fuel, 90 percent S-1 with 10 percent M-2; four spark plugs' spark advance, 22° on three plugs, 19° on fourth plug; piezoelectric pickup in opening I. (See fig. 1.)

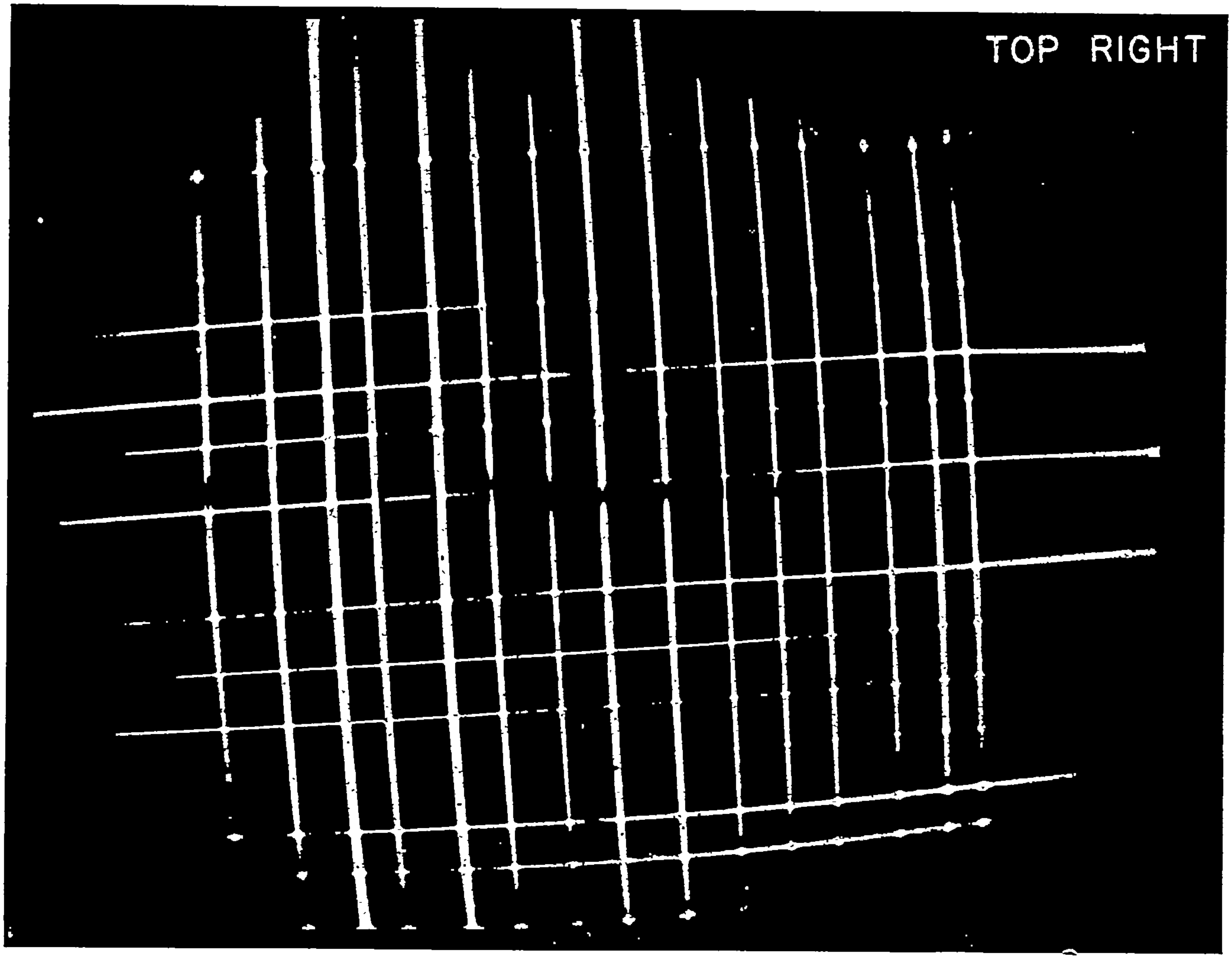


FIGURE 4.—Grid pattern for use in constructing constant-time lines on time-pressure records.

in time. These lines have not been drawn parallel, but each line has been drawn in a direction conforming to the grid pattern shown in figure 4.

The grid of figure 4 was formed by photographing 15 vertical sweeps and 11 horizontal sweeps of the oscillograph beam. With each of the vertical sweeps, the potentials on the horizontal deflection plates were kept constant; with each of the horizontal sweeps, the potentials on the vertical deflection plates were kept constant.

A count of the oscillator cycles between the lines drawn from points F, K, and J reveals that there were 52.4 oscillator cycles between the first and the second timing sparks and that there were 25.1 cycles between the first timing spark and the beginning of the knocking vibrations at the diaphragm of the piezoelectric pickup. This count is probably accurate within one- or two-tenths of a cycle or within one or two motion-picture frames at a camera speed of 40,000 frames per second.

The number of motion-picture frames per oscillator cycle is $\frac{551.5}{52.4}$ or 10.52. The number of motion-picture frames from the first timing spark to the beginning of the knocking vibrations, as shown by the time-pressure record, is therefore 10.52×25.1, or 264. This value is 2½ frames greater than the number of frames exposed between the occurrence of the first timing spark and the exposure of frame I–9 of figure 2, in which the knocking blur is first visible.

An examination of figure 3 reveals that the initial frequency of the knocking vibrations is about 8000 cycles per second, a value that checks with a sound velocity of about 3000 feet per second if the vibrations are assumed to be transverse with one displacement node at the center of the chamber. Using a speed of sound of 3000 feet per second, the time interval of 2½ frames between the exposure of frame I–9 and the beginning of knocking vibrations is found to be only about half enough for the knocking disturbance to travel from the point at which the knocking blur is observed in frame I–9 of figure 2 to the diaphragm of the piezoelectric pickup in opening I of the cylinder head. (See fig. 1.) Results presented later, however, indicate that the 2½-frame value of lag is erroneous.

Figure 5 is a shot of knocking combustion taken under the same conditions as figure 2 but with a blend of 80 percent S–1 and 20 percent M–2 fuels, and figure 6 is the time-pressure record for the same combustion cycle. In this case the knocking blur is first visible at B in frame I–1 of figure 5. One hundred and twenty-three frames are omitted in figure 5 after frame J–18 or before frame A–1.

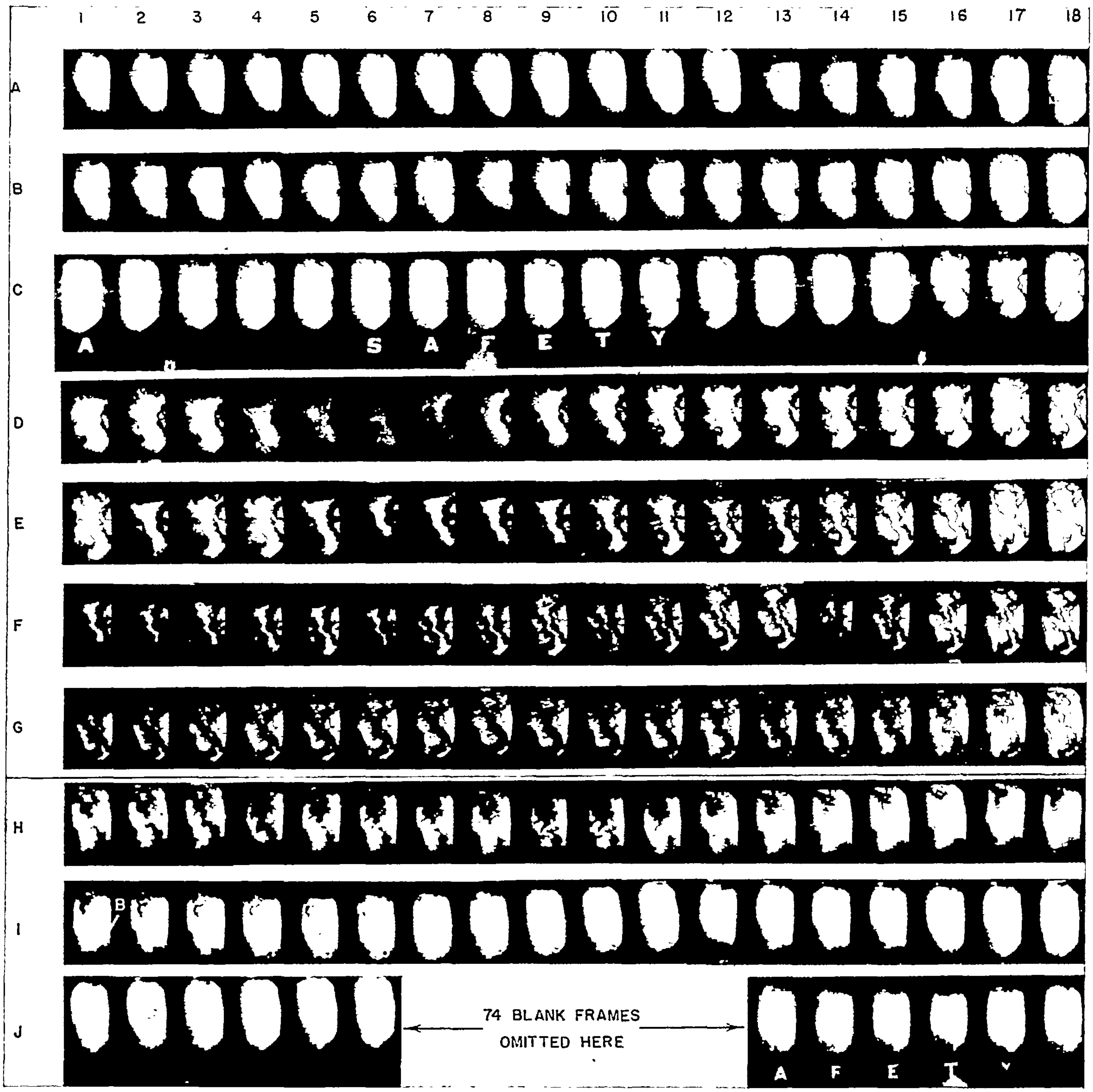


FIGURE 5.—High-speed motion pictures of an explosion in a spark-ignition engine with light knock. Fuel, 80 percent S-1 with 20 percent M-2; four spark plugs; spark advance, left-hand plug, 29°, other three plugs, 22°; B, blurring caused by knock.

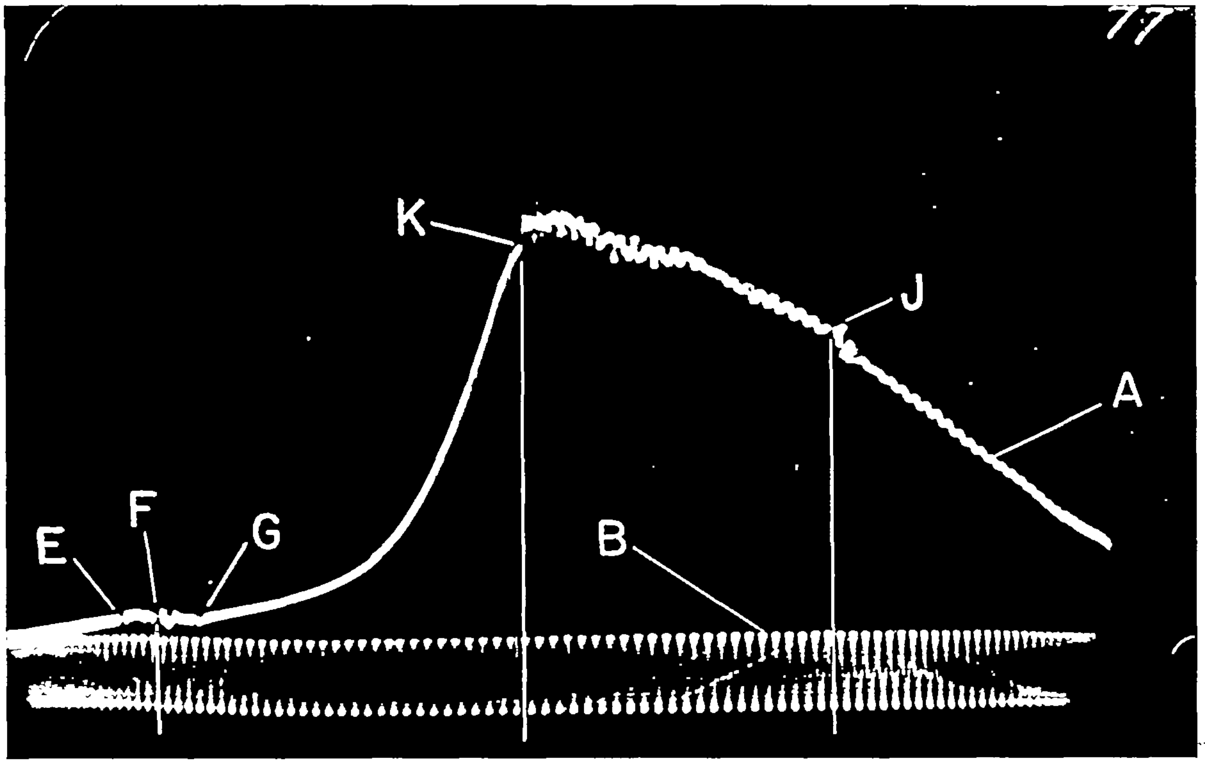


FIGURE 6.—Indicator card with oscillator trace for explosion of figure 5 in a spark-ignition engine with light knock. Fuel, 80 percent S-1 with 20 percent M-2; four spark plugs; spark advance, 22° on three plugs, 29° on fourth plug; piezoelectric pickup in opening I. (See fig. 1.)

Figure 7 is a shot of violently knocking combustion taken under the same conditions as figures 2 and 5 but with a blend of 50 percent S-1 and 50 percent M-2 fuels. Figure 8 is the time-pressure record for the same combustion cycle. The knocking blur is first visible at B in frame F-17 of figure 7. One hundred and fourteen frames were omitted in this figure after frame H-18 or before frame A-1.

The computations of lags between the appearance of blur and the beginning of violent pressure fluctuations for the case of figures 5 and 6 and the case of figures 7 and 8 will be found in table I (a) opposite tests 77 and 95, respectively. The results are 4 frames and 2¼ frames, respectively.

In figure 8, a slight irregularity in the trace before the first of the violent pressure fluctuations appears at M. This irregularity is of the same type as that discussed in reference 7 as being suggestive of the progressive build-up of the knocking vibrations. This irregularity is almost an entire oscillator cycle, or 10½ motion-picture frames, ahead of the first of the violent pressure fluctuations at K. This fact indicates that the irregularity occurred approximately eight motion-picture frames before the exposure of frame F-17 in figure 7, in which the knocking blur is first visible. It might be contended that the possible error involved in the method used in this test for the establishment of time relationship was sufficiently great that the blurring of the mottled zone in frame F-17 of figure 7 actually occurred before the irregularity at M in figure 8. Evidence presented later in this report, however, indicates that the probable error in the 2¼-frame value of lag was not this great.

Table I (a) presents the results of a number of tests made with fuel blends of various antiknock values under the same conditions as the tests of figures 2, 3, and 5 to 8. The only tests omitted from this table are those in which a timing spark failed to occur or which are defective in some other manner such that no determinations can be made from them. No tests with 100 percent S-1 fuel are included because this fuel did not knock under the test conditions.

The number of motion-picture frames between the appearance of the knocking blur and the beginning of the violent pressure fluctuations at the indicator diaphragm is found in column 9 of table I (a). The mean of the values in this column is approximately eight frames and the maximum variation from the mean is six frames. There seems to be no correlation between the number of frames of lag in column 9 and the violence of the knock, controlled by the fuel used. For this reason a smaller number of fuel blends was used in later tests.

The results shown in table I (a) justify a presumption that the violent pressure fluctuations never begin before the appearance of the knocking blur and that they always begin within 4.0×10^{-4} second after the appearance of this blur. The value of the mean lag appears much greater than the time required for the knocking pressure waves to travel from the knocking zone to the diaphragm of the piezoelectric pickup. The variation between individual determinations appears to be much greater than could be explained by personal error and it was believed, therefore, that a more accurate method was needed. In order to establish a more dependable and perhaps a more consistent time relationship, the two-oscillograph method was developed.

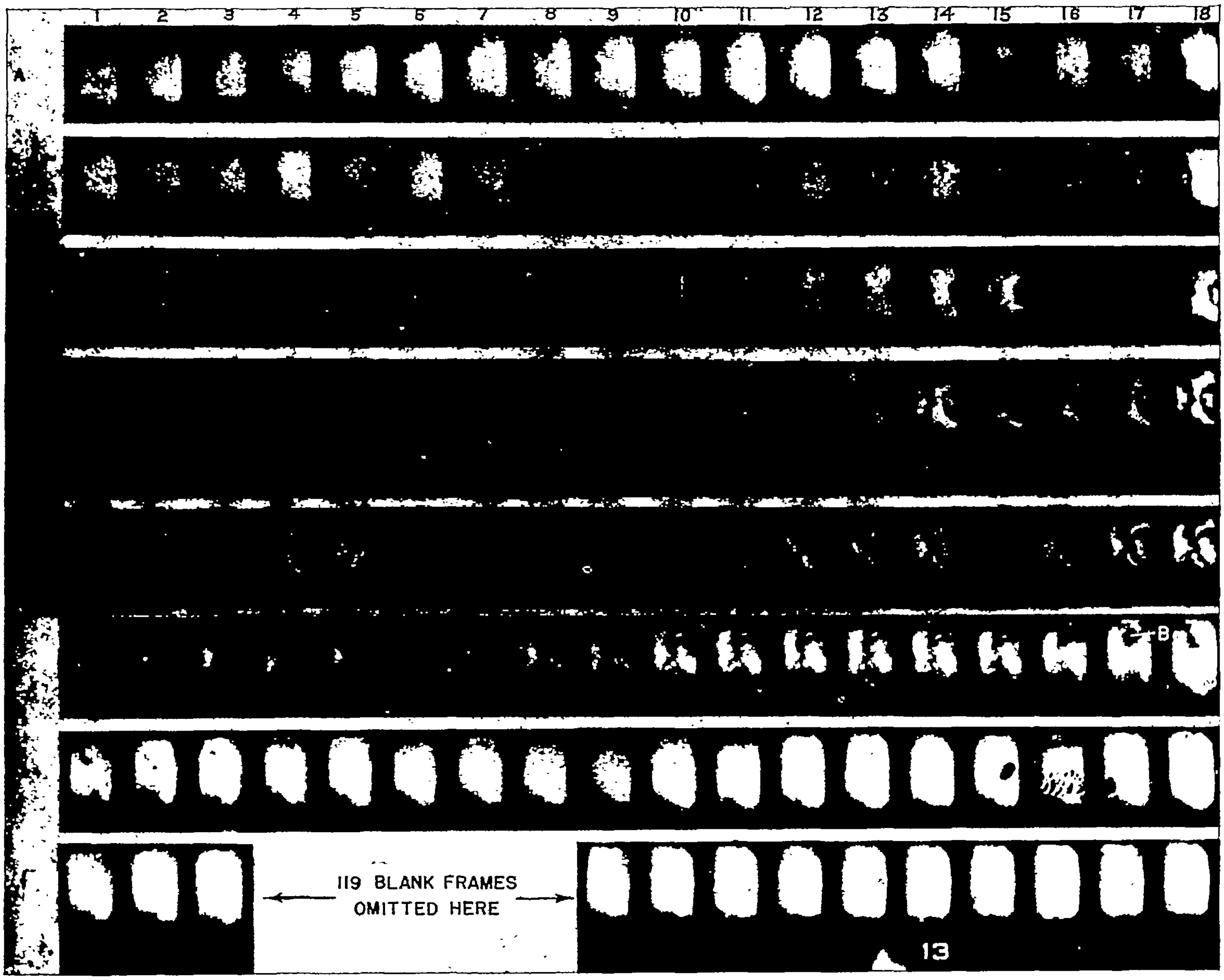


FIGURE 7.—High-speed motion pictures of an explosion in a spark-ignition engine with violent knock. Fuel, 50 percent S-1 with 50 percent M-2; four spark plugs; spark advance, left-hand plug, 29°, other three plugs, 22°; B, blurring caused by knock.

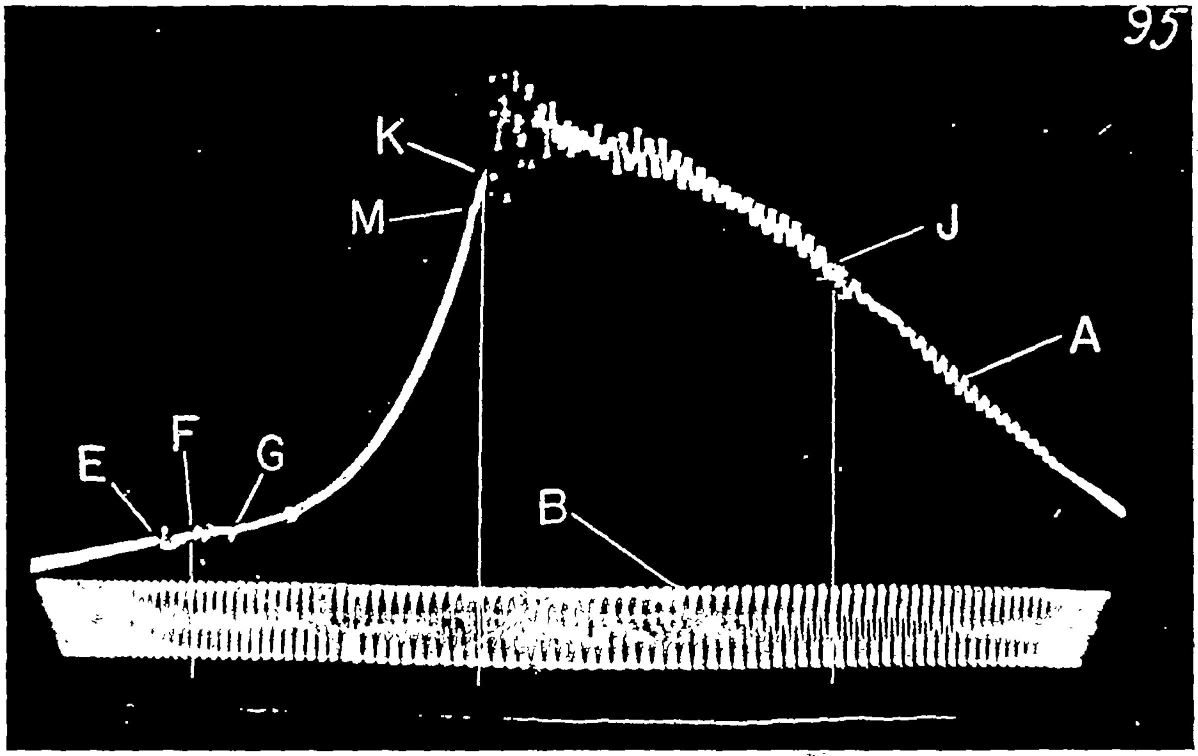


FIGURE 8.—Indicator card with oscillator trace for explosion of figure 7 in a spark-ignition engine with violent knock. Fuel, 50 percent S-1 with 50 percent M-2; four spark plugs; spark advance, 22° on three plugs, 29° on fourth plug; piezoelectric pickup in opening I. (See fig. 1.)

Time relationship of schlieren blur to gas vibrations—second method.—Figure 9 is a photographic series of violently knocking combustion taken under the same conditions and with the same fuel blend as figure 7 but with the two-oscillograph method of establishing time relationship. The characteristic knocking blur occurs in frame I–17 of figure 9. One frame was lost at the splice at frame E–2 and 186 frames are omitted after frame J–17 or before frame A–1. The number of frames between timing sparks is 301, having been reduced, upon changing from the first to the second method, from about 1½ turns of the film drum to a little less than one complete turn of the drum. The first timing spark appears at frame D–7; the second, at frame A–2.

Figure 10 shows the time-pressure record of the combustion cycle photographed in figure 9 combined with the voltage wave delivered by the oscillator. This composite curve is designated A. The oscillator trace alone, also appearing in this figure, is designated B. In each trace the break caused by the first timing spark is designated F and the break caused by the second timing spark is designated J. The break in the time-pressure record caused by the first violent pressure fluctuation is designated K.

In the counting of oscillator cycles between the first timing spark and the break due to violent pressure fluctuations in the trace A of figure 10, consideration must be given to the fact that the peaks due to the oscillator cycles are displaced to the right in the part of the trace in which the pressure rise is rapid. The magnitude of this displacement may be easily calculated from the general slope of the curve, the vertical distance between two successive peaks, and the vertical distance between either of the two successive peaks and the intermediate valley. This calculation does not need to be made, however, for figure 10. The break in the trace at K occurs about halfway between a peak and the probable position of the subsequent valley. Inasmuch as the valleys are displaced to the left by the same amount that the peaks are displaced to the right, the midpoints may be regarded as not displaced.

From trace A of figure 10, a count of the number of oscillator cycles between the first timing spark at F and the break due to violent pressure fluctuation at K yields a value of 12.9. All other steps in the determination of lag between blur in the photographs and the beginning of intense pressure fluctuations at the piezoelectric pickup are the same as with the first method. The determination for the case of figures 9 and 10 may be found in table I (b) opposite test 158. The value of lag is six motion-picture frames.

Table I (b) shows the results of a number of tests made with fuels of various antiknock values under the same conditions as the tests shown in figures 9 and 10. This table includes all tests that are not defective in a manner that renders a determination impossible. Four spark plugs were used for all these tests and the piezoelectric pickup was located in opening I of the cylinder head. (See fig. 1.)

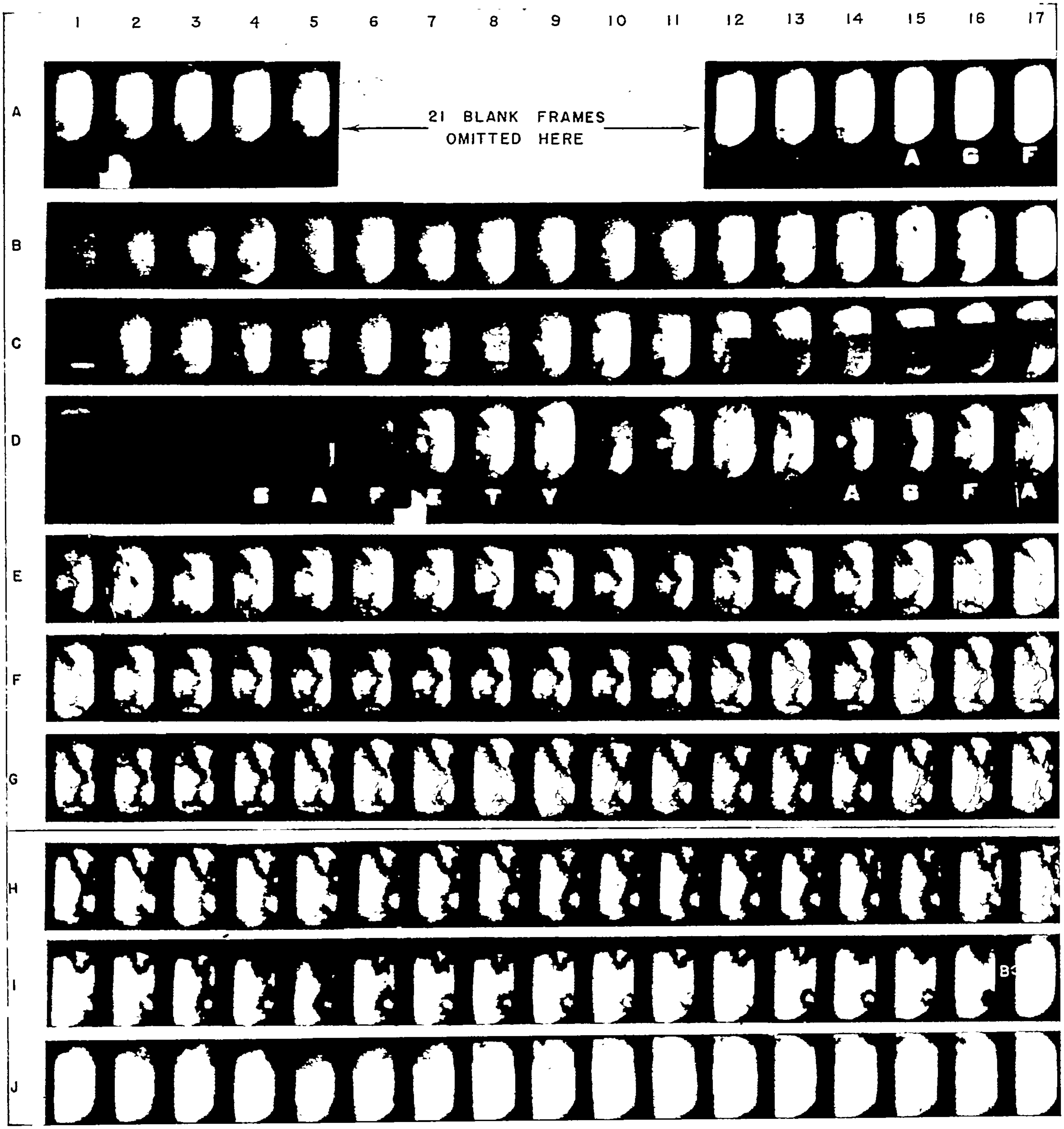


FIGURE 9.—High-speed motion pictures of an explosion in a spark-ignition engine with violent knock. Fuel, 50 percent S-1 with 50 percent M-2; four spark plugs; spark advance, left-hand plug, 29°, other three plugs, 22°; B, blurring caused by knock.

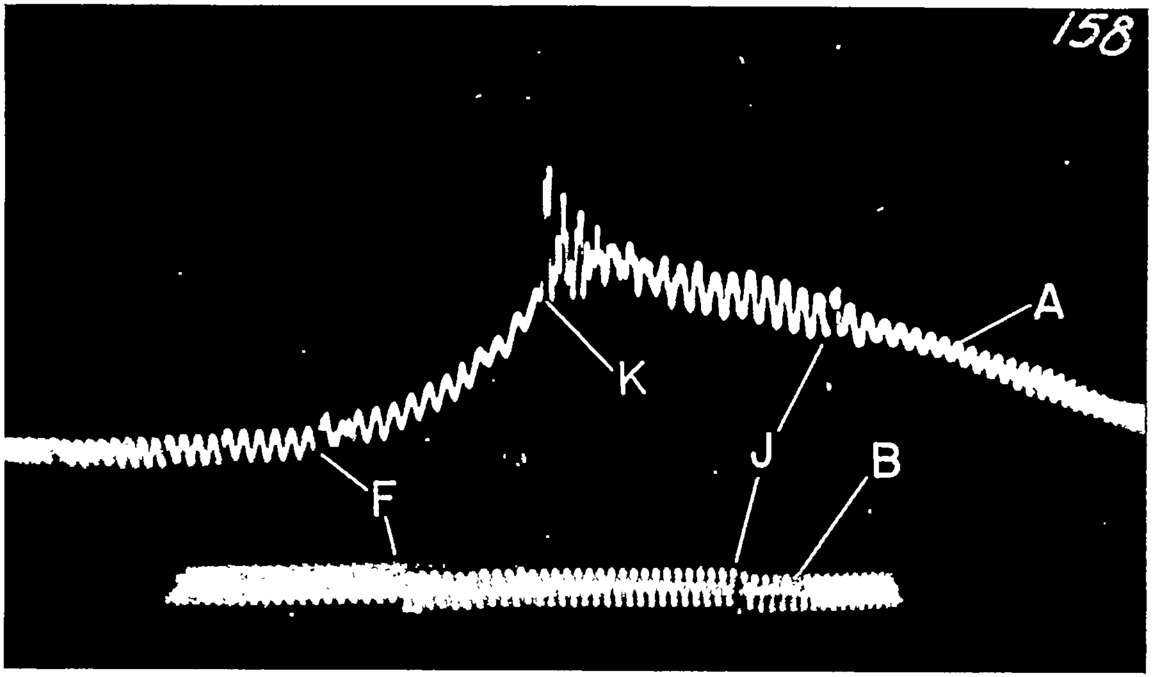


FIGURE 10.—Indicator card combined with oscillator trace and with separate oscillator trace for explosion of figure 9 in a spark-ignition engine with violent knock. Fuel, 50 percent S-1 with 50 percent M-2; four spark plugs; spark advance, 22° on three plugs, 29° on fourth plug; piezoelectric pickup in opening I. (See fig. 1.)

Column 9 of table I (b) shows the time lags between the knocking blur and the beginning of the violent pressure fluctuations at the diaphragm of the piezoelectric pickup. The mean lag in this column is about five motion-picture frames. One value of lag departs from the mean by 1.8 motion-picture frames, or 4.5×10^{-5} second. With the exception of this value the deviations are only about one motion-picture frame. The departure of 1.8 frames from the mean value is probably within the range of possible experimental error.

The five-frame value of mean lag from column 9 of table I (b) is three frames less than the corresponding value from table I (a). The difference is probably due to inaccuracy in the method used to obtain the data of table I (a). The voltage on the vertical deflection plates of the oscillograph appears to have been fed into the horizontal deflection plates to some extent with the result that the time scale was about 7.5×10^{-5} second in error at the time the knock occurred. An independent investigation was made concerning this point with the result that such an effect was found to exist and the effect was found to be not constant. This effect, together with lack of reproducibility of the oscillograph sweep characteristics with constant vertical-deflection-plate voltage, also explains the much greater variation from the mean lag in column 9 of table I (a) than in column 9 of table I (b). The values from table I (b) are undoubtedly far more accurate than those of table I (a).

Figure 11 is a shot of moderately knocking combustion taken with the piezoelectric pickup in opening J, instead of in opening I, of the cylinder head. (See fig. 1.) Figure 12 shows the time-pressure record combined with the oscillator trace and also shows the separate oscillator trace for the same combustion cycle. Three spark plugs were used, in openings F, G, and E. The timing of the spark plugs was adjusted in such a way that the last part of the charge to be ignited was located as close as possible to the diaphragm of the piezoelectric pickup. In figure 11, at about frame I–18, this end gas is almost exactly adjacent to the J opening. The two-oscillograph method was used to determine the time relationship. The fuel was a blend of 80 percent S–1 with 20 percent M–2. Other engine operating conditions were the same as the conditions shown in preceding figures.

In figure 11 the knocking blur first occurs at B in frame J–10. One hundred and sixty-eight frames are omitted from the figure after frame J–18 or before frame A–1. In figure 12 consideration must be given to the displacement of the oscillator cycles on the time-pressure record, inasmuch as the break due to violent pressure fluctuations appears at a valley in the trace. The displacement of the valley in this case is negligible, however, as it amounts to only about two-hundredths of a cycle.

The determination of lag between appearance of blur and beginning of violent pressure fluctuations for the case of figures 11 and 12 may be found in table I (c) opposite test 166. The value of lag in this case is two motion-picture frames.

Table I (c) shows the results of a number of tests made with the two-oscillograph method. The piezoelectric pickup was located in opening J of the cylinder head. (See fig. 1.) The tests of table I (c) were made with fuel blends of two

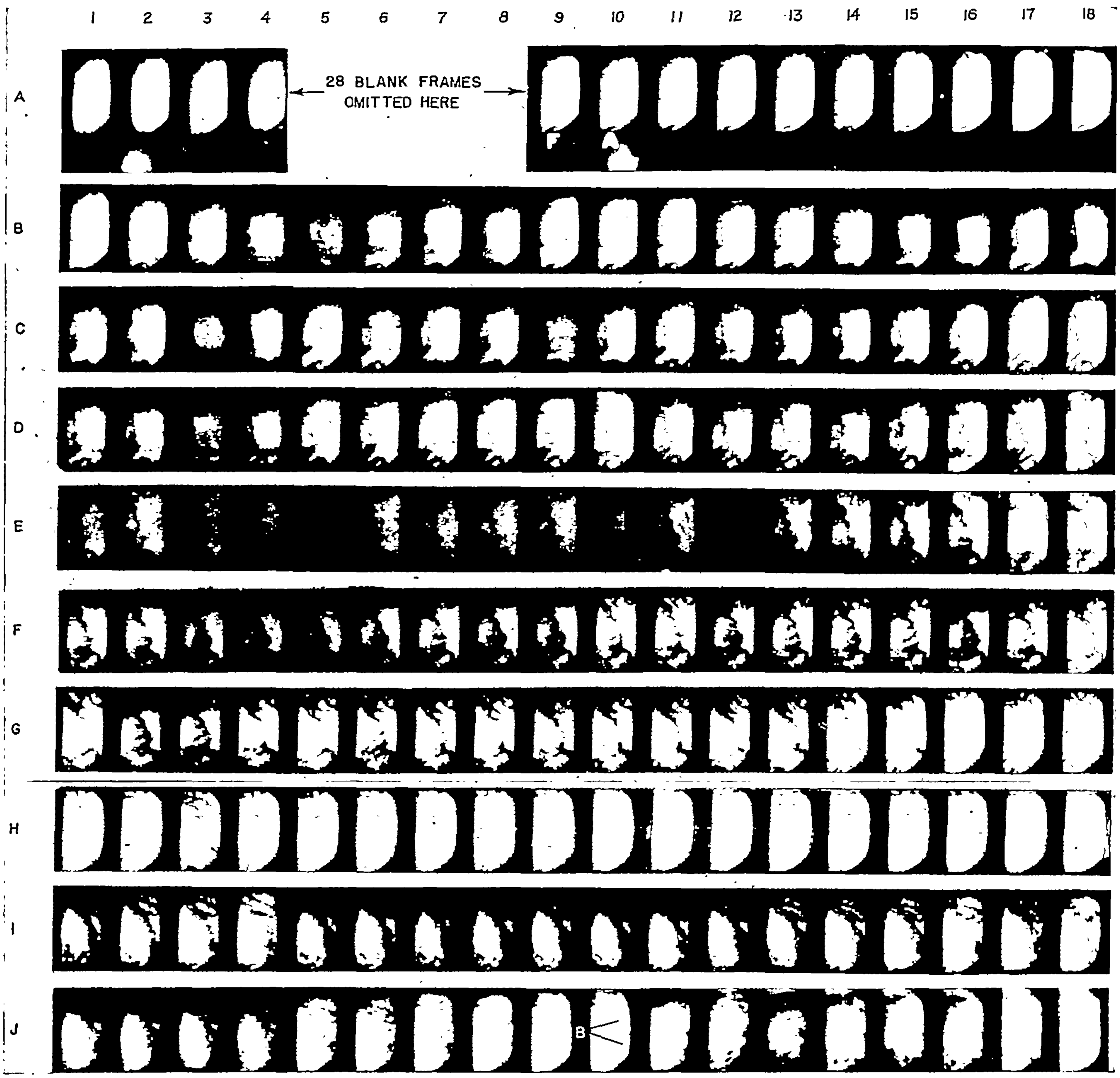


FIGURE 11.—High-speed motion pictures of an explosion in a spark-ignition engine with moderate knock. Fuel, 80 percent S-1 with 20 percent M-2; three spark plugs; spark advance, left-hand plug, 29°, other two plugs, 22°; B, blurring caused by knock.

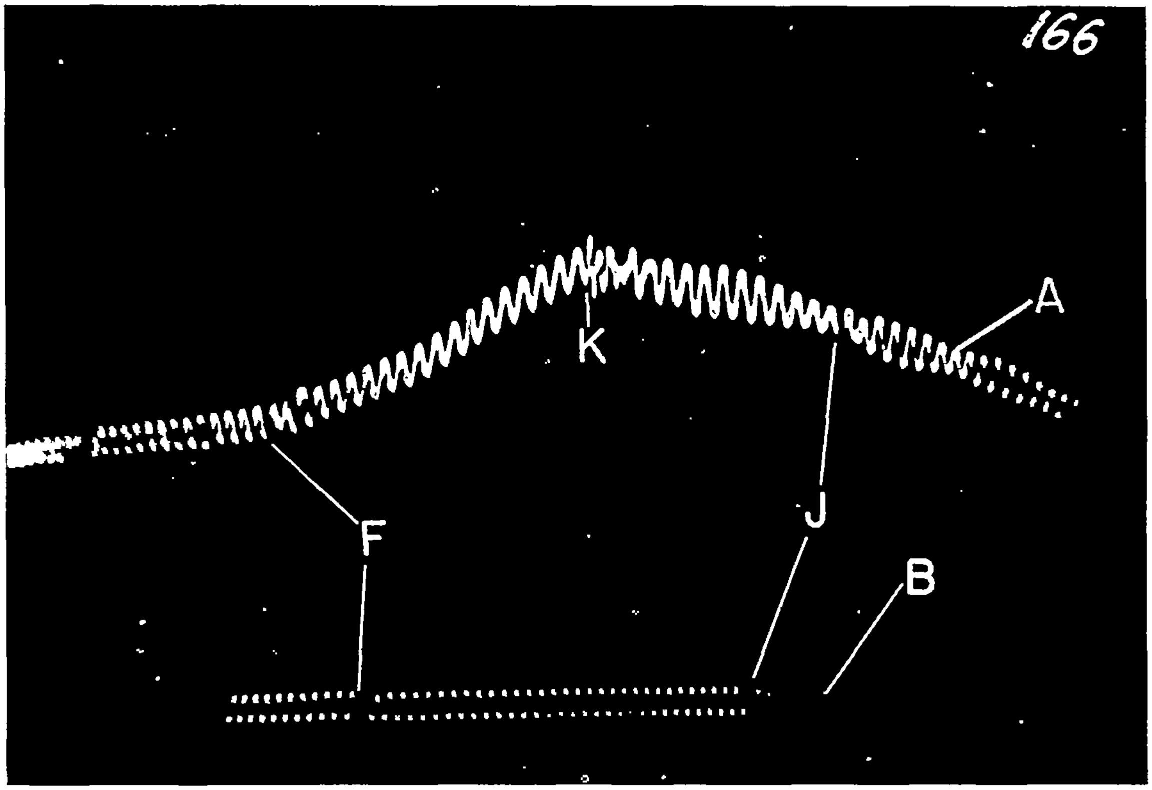


FIGURE 12.—Indicator card combined with oscillator trace and with separate oscillator trace for explosion of figure 11 in a spark-ignition engine with moderate knock. Fuel, 80 percent S-1 with 20 percent M-2; three spark plugs; spark advance, 22° on two plugs, 27° on third plug; piezoelectric pickup in opening J. (See fig. 1.)

different antiknock values. The table includes all tests made under these conditions.

Column 9 of table I (c) shows the time lags between the appearance of the knocking blur and the appearance of violent pressure fluctuation. The mean value is about 1.6 frames or 4.0×10^{-5} second. The maximum departure from the mean value is less than one frame.

A search was made for an explanation of the lag of 1.6 frames between the knocking blur and the beginning of the pressure fluctuations and this lag was accounted for by inaccuracy in the value of 33 frames that was used as the distance between the timing-spark exposure on the film and the motion-picture frame in process of exposure at the time of the spark. The distance from the timing-spark exposure to the center of the photograph-exposure region in the camera was actually almost 33½ frames. The region of photographic exposure in the camera, moreover, is not actually a point but a rectangle with length equal to the combined width of about three frames. The camera has a focal-plane-shutter effect that causes the knocking region in the photographs to be exposed after it has passed the center of the exposure region by about the width of one frame. These two sources of error account, within one-tenth frame, for the lag of 1.6 frames.

The difference in mean lag between the values of tables I (b) and I (c) is 3.6 motion-picture frames. With the probable sound velocity of about 3000 feet per second, a pressure wave would travel 3¼ inches during the time of 3.6 motion-picture frames. This distance checks well with the distance from end zone to the piezoelectric pickup when the pickup was in opening I of the cylinder head and four spark plugs were used.

The results shown in tables I (b) and I (c) establish with remarkable precision the fact that the knocking blur in the high-speed pictures coincides in time with the beginning of the violent knocking vibrations. It therefore appears to be a reasonable conclusion that the knocking blur represents the physical aspect of a chemical reaction which is the actual cause of the knocking vibrations. This reaction takes place in 2.5×10^{-5} second or less with light, violent, or intermediate knocks and its establishment as the origin of knocking vibrations shows conclusively that the type of knock encountered under the conditions of these tests is a phenomenon distinct from the slow combustion resulting from autoignition, photographed by the authors of reference 4, which covers a time of about 1.0×10^{-3} second, many times greater than 2.5×10^{-5} second.

Time relationship between preliminary pressure fluctuations of small amplitude and periodic variations in configurations of photographs.—With the very precise establishment of coincidence in time of the knocking blur and the beginning of the violent pressure fluctuations, the conclusion follows that the small-amplitude pressure fluctuations discussed in reference 7, which occupy the period of about 4.0×10^{-4} second immediately preceding the violent pressure fluctuations that are caused by heavy knock, must also precede the knocking blur. The small-amplitude fluctuations must therefore cover the same period of time as the periodic variations of the configurations in the photographs, which were reported in reference 7. These periodic varia-

tions have been observed in the few frames covering approximately the same period of about 4.0×10^{-4} second immediately preceding the knocking blur when the original negatives were examined, frame by frame, on a projection screen. They are not readily observed in the reproductions printed in the reports. The establishment of coincidence in period of time between these small-amplitude pressure fluctuations and the periodic variations in the configurations of the photographs lends further weight to the theory of the progressive build-up of the knocking waves. No attempt has yet been made to correlate particular variations of configurations in the high-speed photographs with particular irregularities in the time-pressure record.

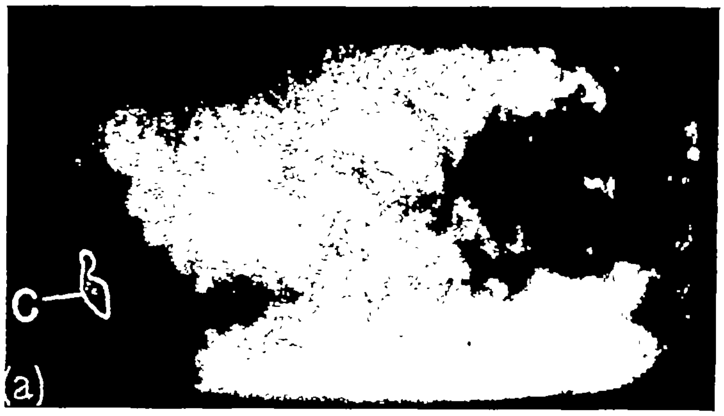
Position of knocking blur relative to end zone.—Figure 13 presents greatly enlarged views of two frames, G–11 and I–9, from figure 2. Frame G–11 was exposed while a part of the cylinder charge had not yet been reached by the flame fronts. This part of the charge has been outlined with white ink in the enlarged view of frame G–11 in figure 13 (a) and has been designated C. The same outline has been superposed on the enlarged view of frame I–9 in figure 13 (b). In this last-mentioned frame, the blurred region has been outlined and designated B. The two outlined regions overlap only slightly and are displaced from each other in a direction at right angles to the direction of displacement observed in figures 8 and 9 of reference 7.

A similar comparison of frames H–11 and I–1 of figure 5 is presented in figure 14. At the time of exposure of frame H–11, only a very small part of the charge had not yet been reached by the flame fronts. In figure 14 (b) this end zone will be seen not even to overlap the blurred region. The displacement, again, is in a direction at right angles to that observed in figures 8 and 9 of reference 7.

(a) Frame G–11 from figure 2. Flame has not yet reached area within outline C.

(b) Frame I–9 from figure 2. Knock has just occurred. Blurring within outline B is caused by knock.

FIGURE 13.—Two periods in the course of an explosion in a spark ignition engine with very light knock.



(a) Frame H-11 from figure 5. Flame has not yet reached area within outline C.

(b) Frame I-1 from figure 5. Knock has just occurred. Blurring within outline B is caused by knock.

FIGURE 14.—Two periods in the course of an explosion in a spark-ignition engine with light knock.

In the discussion of figures 8 and 9 of reference 7, mention was made of the fact that the camera has a focal-plane-shutter effect which would tend to cause the displacement observed in those figures. In figures 13 (b) and 14 (b) of the present report, however, the displacement is in a direction at right angles to the direction of the focal-plane-shutter effect. The displacement must therefore be regarded as actually having existed within the combustion chamber.

At the time knock occurred in figures 13 (b) and 14 (b), pockets of unignited gas might be held to exist in the regions designated B, although such a contention would require a more marked tonguing of the flames than is observed in the visible projection. It seems a fair presumption, however, that thicker pockets of unignited gas would exist in the regions designated C than in the regions designated B. For this reason, an explanation of the displacement based on the simple autoignition theory is difficult.

The displacement observed in figures 13 and 14 can be explained satisfactorily on the theory that knock is a reaction which takes place in the burning gas rather than in the unignited gas and that this reaction results in a very rapid

completion of combustion. Immediately before the exposure of the frames shown in figures 13 (b) and 14 (b), combustion should be much nearer completion in the regions designated B than in the regions designated C. If the knocking reaction proceeds toward a completion of the combustion at a uniform rate throughout the combustion zone, the regions that are most nearly burned at the time the knock starts should be expected to clear up first. This explanation is based on the assumption that the mottled region in the photographs is coincident with the combustion zone and that the knocking blur is simply a disappearance of the mottled region.

The explanation of the preceding paragraph might also apply with the theory of progressive build-up of a reflected wave discussed in reference 7.

Significance of mottled zone.—Figure 15 is a shot of non-knocking combustion taken with the single-oscillograph method of establishing time relationship. Four spark plugs were used in such a manner that the end zone is within the field of view. The end zone is divided into two parts at about frame D–20 by the merging of the flames from the spark plugs in G and J positions. (See fig. 1.) Both the upper and lower parts of the end zone are finally consumed by the flame fronts within the field of view at about frame F–18. The last trace of mottling does not disappear, however, until about frame J–1. The dark region in the upper parts of the frames following J–1 is due to defects in the glass windows and is not schlieren mottling produced by the gases in the combustion chamber.

Three frames are missing from figure 15 at the splice at frame J–2. Ninety-five frames were omitted from the figure before frame A–1 or after frame J–22. The first

FIGURE 15.—High-speed motion pictures of an explosion in a spark-ignition engine without knock. Fuel, S-1; four spark plugs; spark advance, left-hand plug, 29°, other three plugs, 22°

timing spark was exposed, before the camera began taking pictures, at frame J–18 and the second timing spark was exposed 549 frames later, after the camera had ceased taking pictures, at frame D–12.

Figure 16 is the time-pressure record A with independent oscillator trace B for the nonknocking explosion shown photographically in figure 15. The point of peak pressure was selected as H. Other designated points are as shown in the previous figures. The lag between final complete fade-out of the mottled zone and the attainment of peak pressure is calculated opposite test 65 in table II as 10 motion-picture frames. In this case no correction is required for the effect of piston movement on pressure. The first timing spark occurred 26° B. T. C., and the second timing spark occurred 14° A. T. C. The point H in the time-pressure trace of figure 16 was therefore reached at 1.4° B. T. C. A point only two oscillator cycles ahead of point H in the trace will be observed to be at an appreciably lower pressure than the point H. The two oscillator cycles amount to about 1.5° of crankshaft rotation; consequently, the pressure in the combustion chamber must have been appreciably increased between 2.9° B. T. C. and 1.4° B. T. C. The increase in pressure due to adiabatic compression by piston movement between 2.9° B. T. C. and 1.4° B. T. C. would be far less than the minimum increment that could be measured by the apparatus used for obtaining the results shown in figure 16. The results shown in table II are of considerable interest relative to the significance of the mottled zone in the photographs. This table shows the results of a number of tests with nonknocking combustion similar to that of figures 15 and 16. All these tests were made with S–1 fuel. Four spark plugs were used in each case and the end zone was always within the field of view. In all cases the spark advance and the crank angles at which the timing sparks occurred were the same as in figures 15 and 16. Peak pressure was reached in each case within 1° or 2° of top center. The table includes all tests made under these conditions. The original selections of point of peak pressure and motion-picture frame of final fade-out of mottled zone were adhered to in each case.

Column 8 of table II gives the time lags in motion-picture frames between the final fade-out of the mottled zone in the schlieren photographs and the occurrence of peak pressure.

Rocking of the piston when passing over top center prevents an extremely precise adjustment of the schlieren setup because the mirror on top of the piston forms a part of the setup. For this reason, the fade-out of the mottled zone should not be expected to occur in all photographs at precisely the same conditions of the gas within the chamber. When this fact is considered, as well as the difficulty of picking the precise peak of the time-pressure curve and the precise frame in which schlieren mottling disappears, the agreement of the values in column 8 of table II appears very remarkable.

The conclusion appears to be justified, at least for the end of the combustion process, that the schlieren mottling indicates continuance of the process of combustion, if "combustion" is defined as representing all stages of the conversion of chemical energy of the gas mixture into pressure energy in the combustion chamber. Conversely, the conclusion appears justified that very little combustion not

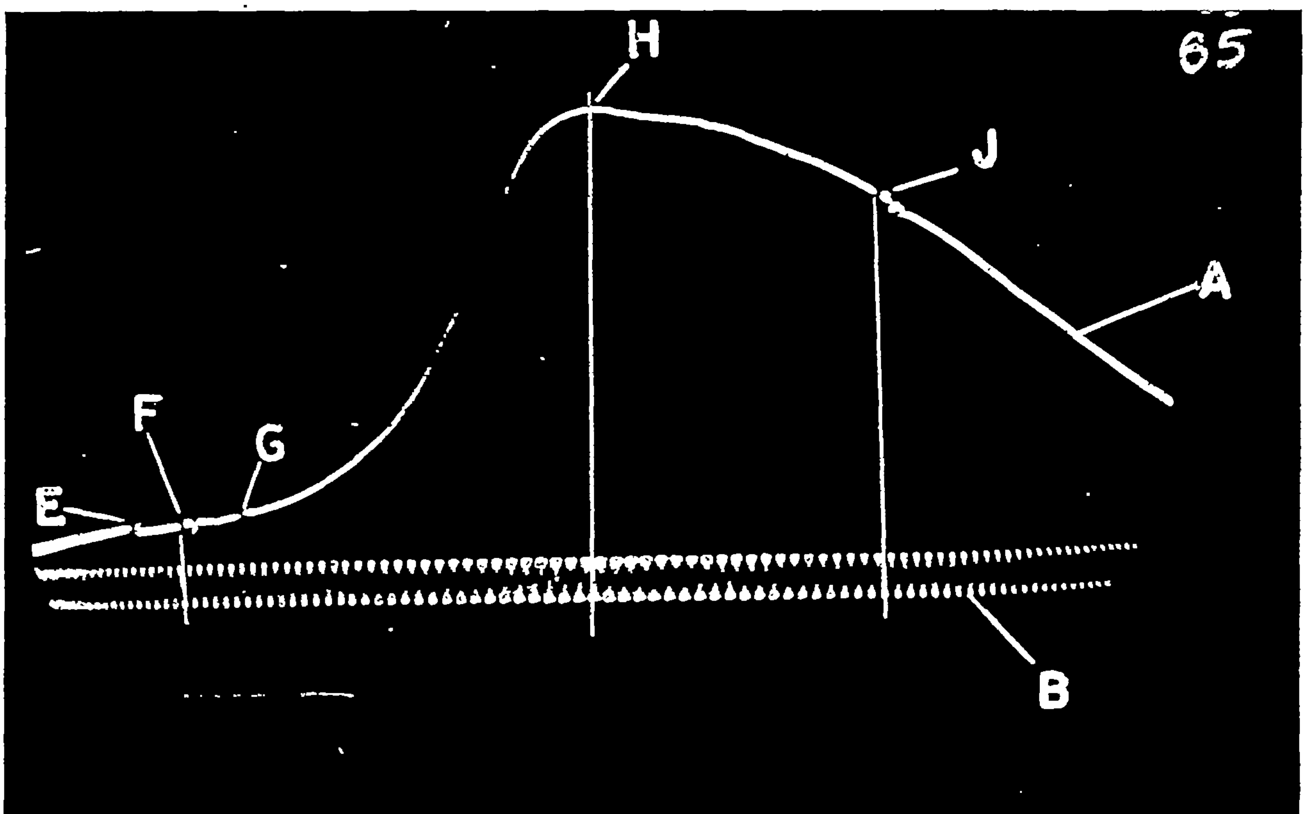


FIGURE 16.—Indicator card with oscillator trace for nonknocking explosion in a spark-ignition engine. Fuel, S-1; four spark plugs; spark advance, 22° on three plugs, 29° on fourth plug.

indicated by the schlieren mottling takes place. In the absence of evidence to the contrary, a fair presumption seems justified that the mottling indicates existence of the process of combustion in the early stages also. Moreover, the term "combustion" as used in this paragraph should be understood to mean reaction at a rate of the same order as that existing in the normal flames.

Explanation of the existence of the schlieren mottling on the basis of extremely thin curved flames requires the assumption of much more pronounced flame tonguing than has ever been observed in the visible projection. The results presented in table II, therefore, strongly indicate that the assumption of extremely thin combustion zones is incorrect, at least during the early stages of flame travel.

In all photographs of knocking combustion obtained with the NACA high-speed camera, one or the other of the following conditions has been observed:

(*a*) The flame fronts have appeared to pass through all parts of the cylinder charge before the occurrence of knock. (See figs. 4, 6, and 10 of reference 7 and figs. 2 and 5 of this report.)

(*b*) Mottling has appeared in the end zone ahead of the flame fronts an appreciable time before the occurrence of the characteristic blur which has been identified herein as knock. (See figs. 5 and 8 of reference 1, fig. 7 of reference 7, and figs. 7, 9, and 11 of this report.)

It appears likely, therefore, with the previously justified presumption that mottling in the photographs indicates the existence of combustion, that knock does not occur until all parts of the charge have been ignited either by autoignition or by passage of the flame fronts. In some cases the autoignition appears to have taken place only one or two frames before the knock; in other cases it occurred many frames earlier. On the other hand, the results presented in tables I (b) and I (c) indicate clearly that knock takes place in the general end zone under the conditions of these tests. The evidence is fairly conclusive, therefore, that spark-ignition fuel knock of the types studied in this report and references 1 and 7 is a reaction taking place only in a part of the charge that is inflamed but that is not yet completely burned.

With the second method of establishing time relationship, in all cases where mottling has preceded the knocking blur by more than one or two motion-picture frames the results show that the mottling also preceded the beginning of the violent pressure fluctuations. When the mottling occurred only one or two motion-picture frames before the knocking blur, conclusive proof that its occurrence also preceded the beginning of the violent pressure fluctuations could not, of course, be obtained.

CONCLUSIONS

The test conditions for the experiments of the present report included only one value of compression ratio and only one type of fuel. Usual engine operating conditions were not reproduced, inasmuch as the fuel charge was injected into the cylinder on the intake stroke and residual combustion products were not present in the chamber. The possibility exists that knock may take on different aspects under different conditions and the following conclusions should therefore be considered definite only for conditions approximating those of the tests:

1. The characteristic blurring in the NACA high-speed photographs of knocking combustion coincides in time with the start of knocking vibrations. The blurring may therefore be considered a result of the knocking reaction.

2. The preliminary pressure fluctuations of small amplitude that precede the violent knocking vibrations occur during the same period of time as the periodic variations in the configurations of the schlieren mottling, which have been observed on the projection screen.

3. The first evidence of knocking reaction is sometimes in a different position from the last part of the charge to be ignited, although always in the general end zone.

4. The knocking reaction can apparently originate in any region in which combustion is continuing, whether this is the last portion to be ignited or not. Knock apparently originates only in a part of the fuel charge that has been previously ignited, either by autoignition or by passage of the flame fronts, but which has not burned to completion.

5. The mottling in the high-speed photographs undoubtedly coincides with the regions in which combustion is taking place. Serious doubt is therefore cast upon the theory that combustion is completed within an extremely thin flame front inasmuch as the mottling extends far back of the flame front.

6. Inadequacy of the simple autoignition theory of knock is indicated.

Aeronautical Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, *November 14, 1942.*

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TABLE I

DETERMINATIONS OF TIME LAGS BETWEEN OCCURRENCE OF BLURRING IN HIGH-SPEED PHOTOGRAPHS OF KNOCKING COMBUSTION AND THE BEGINNING OF VIOLENT PRESSURE FLUCTUATIONS IN COMBUSTION CHAMBER

1	2	3	4	5	6	7	8	9
Test	Fuel (percentage of S-1 in blend with M-2)	Motion-picture frames between sparks	Oscillator cycles between sparks	Motion-picture frames per oscillator cycle	Oscillator cycles from first timing spark to initiation of intense pressure fluctuations	Motion-picture frames from first timing spark to initiation of intense pressure fluctuations	Motion-picture frames from first timing spark to knocking blur	Motion-picture frames between knocking blur and initiation of intense pressure fluctuations
(a) Single-oscillograph method of determining time relationship; piezoelectric pickup opposite end zone								
70	90	544	52.2	10.46	28.8	300	291	9
71	90	545	52.7	10.35	25.6	265	259	6
72	90	552	52.4	10.53	25.1	264	262	2
73	90	554	53.9	10.28	28.7	295	290	5
74	90	550	53.0	10.38	27.1	281	270	11
75	90	546	53.0	10.30	27.1	279	265	14
76	80	579	55.0	10.53	31.8	335	325	10
77	80	542	52.0	10.42	29.5	307	303	4
78	80	570	54.1	10.54	28.5	300	289	11
79	80	567	54.2	10.47	27.7	290	287	3
80	80	545	52.0	10.48	27.0	283	274	9
81	70	580	55.3	10.49	27.5	288	279	9
83	70	553	53.9	10.27	26.9	276	267	9
84	70	566	54.3	10.41	30.6	318	312	6
86	70	569	54.9	10.37	27.9	289	280	9
87	60	545	52.8	10.33	27.7	286	273	13
88	60	546	53.7	10.18	28.0	285	276	9
89	60	560	54.0	10.38	25.1	260	255	5
90	60	566	53.7	10.47	26.2	276	271	5
91	60	576	53.7	10.54	25.6	260	255	5
92	50	564	54.1	10.42	27.2	283	274	9
93	50	575	55.5	10.37	25.5	264	255	9
94	50	572	53.9	10.61	22.8	242	231	11
95	50	547	51.8	10.56	24.9	263	260	3
96	40	547	53.0	10.31	23.6	243	238	5
97	40	575	54.8	10.58	27.2	288	280	8
99	40	570	54.7	10.42	23.1	241	237	4
100	40	542	52.2	10.38	24.9	258	249	9
103	30	538	51.7	10.41	22.8	238	232	6
104	30	567	53.7	10,56	25.5	269	261	8
105	30	561	53.1	10.57	20.8	220	217	3
106	30	562	54.4	10.33	22.8	236	228	8
107	30	575	54.6	10.53	22.0	232	227	5
108	20	566	54.2	10.43	21.1	220	215	5
109	20	570	54.4	10.48	22.3	234	223	11
111	20	556	53.9	10.32	25.2	260	246	14
112	20	563	54.6	10.31	24.1	249	238	11
113	10	555	54.3	10.22	20.4	208	200	8
114	10	547	52.6	10.39	22.8	237	229	8
115	10	551	52.8	10.42	22.6	236	225	11
116	10	549	52.7	10.41	21.6	225	215	10
117	10	552	52.5	10.41	23.6	248	234	14
118	0	555	52.6	10.56	22.0	234	225	13
119	0	555	52.6	10.56	21.9	231	225	6
120	0	551	52.3	10.52	21.3	225	214	11
121	0	547	52.4	10.43	23.7	247	240	7
122	0	550	53.5	10.29	21.5	221	214	7
(b) Two-oscillograph method of determining time relationship; piezoelectric pickup opposite end zone								
146	80	301	28.9	10.41	11.8	123	117	6
147	80	301	29.0	10.38	13.5	140	134	6
148	80	308	29.6	10.41	16.2	169	164	5
149	80	308	29.6	10.40	17.8	185	180	5
152	80	304	29.3	10.38	13.6	141	136	5
153	50	305	29.6	10.31	10.4	107	101	6
154	50	307	29.5	10.41	10.4	108	104	4
155	50	305	29.4	10.38	11.6	121	116	5
156	50	314	30.1	10.43	12.1	126	121	5
157	50	312	30.0	10.40	10.5	109	105	4
158	50	301	29.0	10.38	12.9	134	128	6
159	0	311	29.7	10.43	6.3	66	60	6
160	0	307	29.3	10.48	9.5	100	95	5
161	0	314	30.4	10.33	11.7	121	117	4
162	0	325	31.2	10.41	10.0	104	100	4
163	0	323	31.3	10.32	11.5	119	112	7
(c) Two-oscillograph method of determining time relationship; piezoelectric pickup at end zone								
164	80	343	31.1	10.33	17.6	182	180	2
165	80	341	32.9	10.37	16.3	169	168	1
166	80	340	32.8	10.37	19.0	197	195	2
167	80	338	32.6	10.37	18.8	195	194	1
168	80	349	33.7	10.36	16.7	173	171	2
169	50	333	32.2	10.35	17.0	176	175	1
170	50	331	32.2	10.29	12.5	129	127	2
171	50	333	32.4	10.29	15.3	157	155	2

TABLE II

DETERMINATIONS OF TIME LAGS BETWEEN FINAL FADE-OUT OF MOTTLED ZONE IN HIGH-SPEED PHOTOGRAPHS OF NONKNOCKING COMBUSTION AND ATTAINMENT OF MAXIMUM PRESSURE WITHIN THE COMBUSTION CHAMBER

1	2	3	4	5	6	7	8
Test	Motion-picture frames between timing sparks	Oscillator cycles between timing sparks	Motion-picture frames per oscillator cycle	Oscillator cycles between first timing spark and peak pressure	Motion-picture frames between first timing spark and peak pressure	Motion-picture frames between first timing spark and final fade-out of mottled zone	Motion-picture frames between final fade-out of mottled zone and peak pressure
63	574	56.1	10.23	35.0	358	345	13
64	552	53.1	10.39	32.4	337	337	0
65	549	52.0	10.56	32.0	338	328	10
66	551	52.4	10.51	30.0	315	320	−5
67	546	52.1	10.48	29.6	310	308	2